Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Intra-body Communication for In Vivo Wireless Nano-sensor Networks

From Micro to Nano: The Evolution of Healthcare

Raed Shubair

Abstract: The emerging intra-body communication (IBC) and networking system is a prospective component in advancing healthcare delivery and empowering the development of future medical monitoring systems. Using the human body as a transmission medium unfastened the research perspective towards Human Body Communication which has been introduced by the IEEE as a third physical layer. Generally, there are two approaches of HBC, namely, capacitive coupling and galvanic coupling. In this paper, the concept of galvanic coupling is adopted as a method for wireless transmission inside the human body. Then, the channel characteristics of the HBC based on the IEEE 802.15.6 standards are addressed where we focus on both the frequency response and the noise characterization. The results obtained are necessary for developing a realistic human body channel model capable of estimating the performances of wearable systems using HBC technology.

Keywords: Intra-body communication (IBC), human body communication (HBC), channel characterization, WBAN.

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From Micro to Nano: The Evolution of Healthcare

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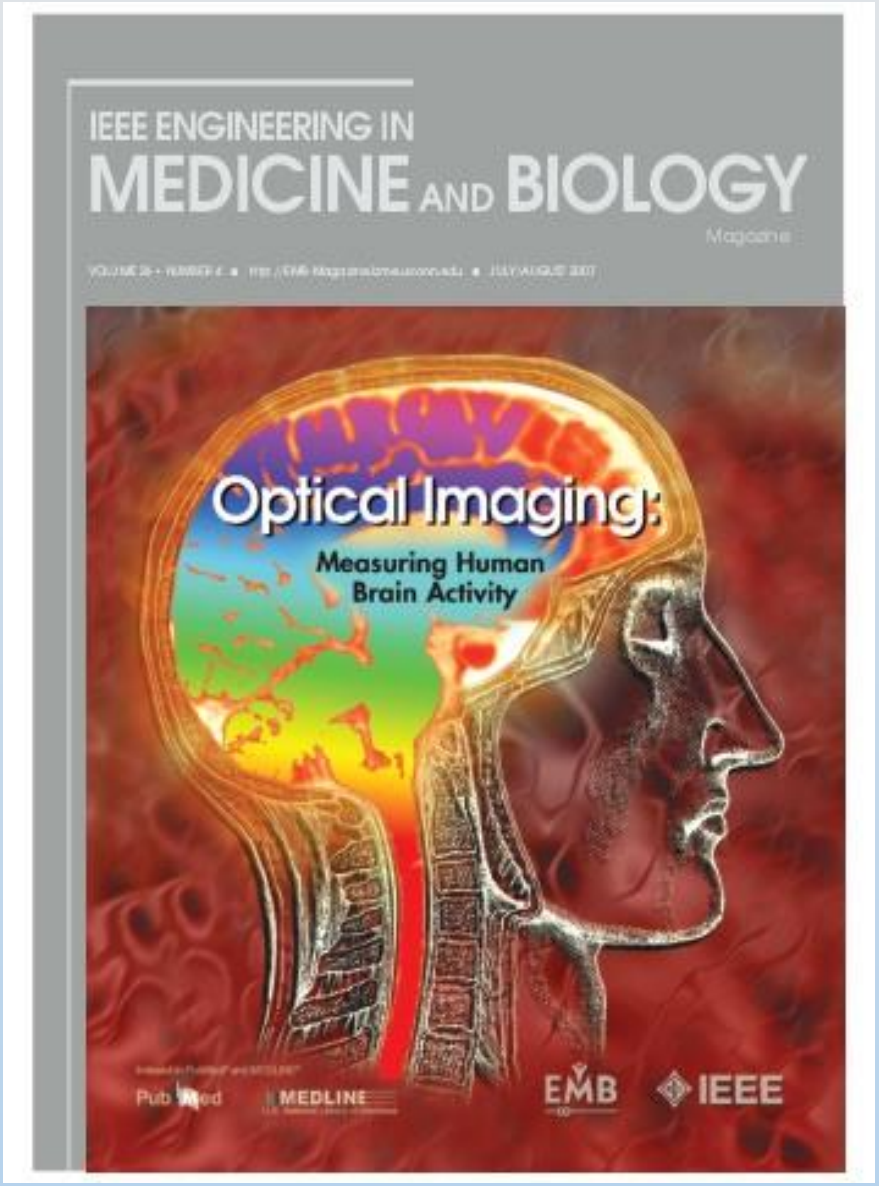
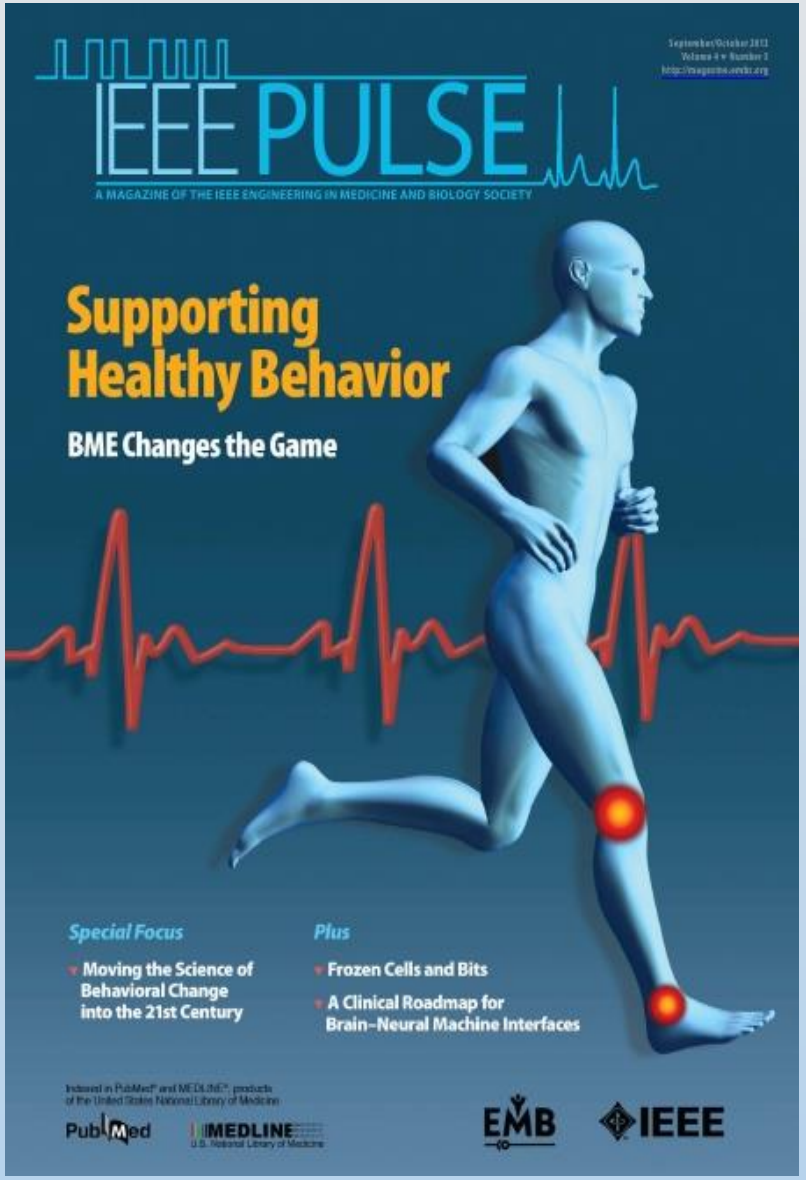
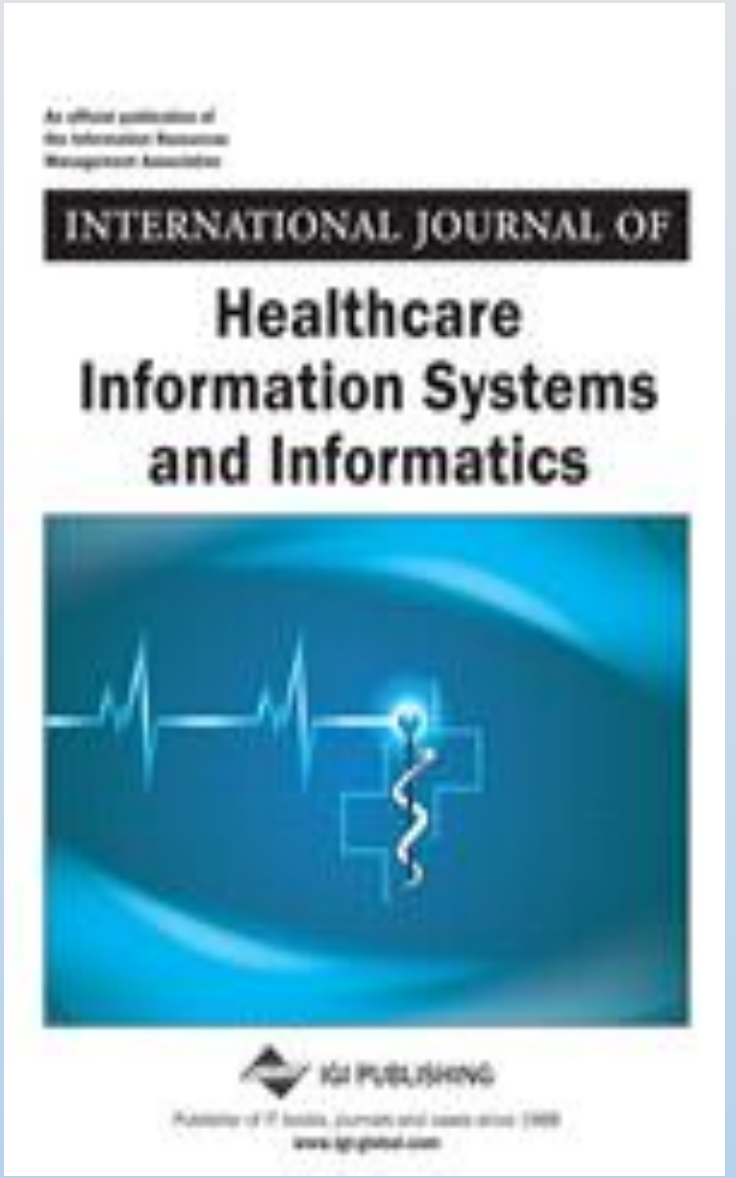
Nanotechnolgy: Big Things from a Tiny World!







Cancer Therapy Through Nanomedicine

The National Cancer Institute's plan to defeat cancer through engineered design.

GEORGE W. HINKAL, DOROTHY FARRELL, SARA S. HOOK, NICHOLAS J. PANARO, KRZYSZTOF PTAK, AND PIOTR GRODZINSKI

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- **Sensors of a micro-scaled WBAN:**
  - Unable to provide absolute invasive medical care (*inconvenient as it requires piercing and penetration of the patient's body*).
  - Fail to provide cellular-level precision in measurement and actuation.

- **The advancements in nanotechnology provided a solution to the limitations of the microscale WBAN-based health care**.
  - Nanotechnology enables fabrication of devices in the scale of 1 to 100 nm.
  - These nanodevices are envisioned as a tiny arranged set of molecules able to perform small and simple sensing, actuation, and computation tasks.
  - As proposed by Akyildiz et al., a nanosensor node consists of multiple nanocomponents, each designed to perform a particular task.

• Network Topology

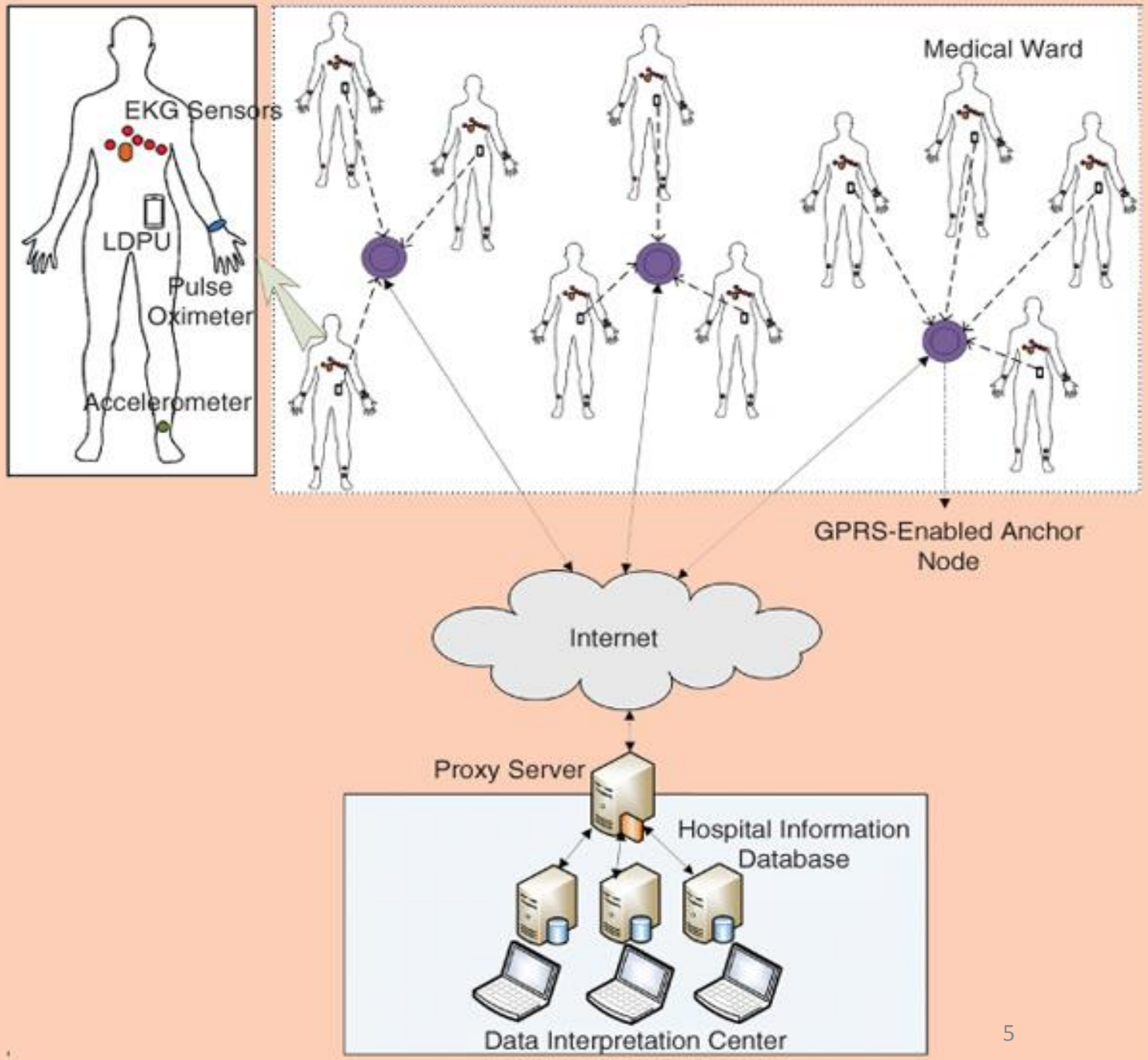
- Nanocomponents form a wireless nanobiosensor network

- Sensors communicate via nanoscale data-acquisition module

- Communications among the nanosensor nodes do not follow the existing wireless communication protocols

- The difference between a traditional sensor network and a nanobiosensor network is the :

Modes and Medium of Communication



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Application Areas of Wireless Nano-Biosensor Networks

Health Monitoring

- Measure pH at two different places within a single cell.
- Measure oxygen and cholesterol levels
- Identify of cancerous cells
- Diagnose hormonal disorders

Drug Delivery

- Smart nanoactautors deliver drugs invasively without external interference .

Examples

- Smart insulin nanoactuators can constantly monitor the blood sugar level and inject precalculated amounts of insulin.
- Cellular-level chemotherapy

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Application Areas of Wireless Nano-Biosensor Networks

Immunity Support

- Identify the presence of foreign bodies and pathogens within the human body.
- Capable of responding against the malicious cells, resulting in disease treatment that is **localized, less aggressive, and less invasive**.

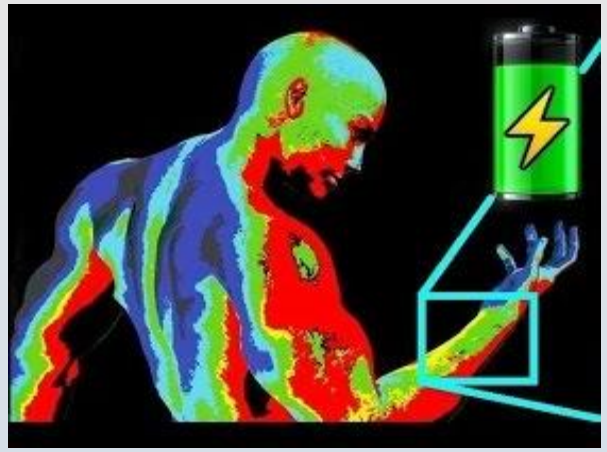
Medical Imaging

- Diagnostic and stem cell imaging

Other Applications

- Deep brain nano-stimulators

Three Main Research Areas
(From an Engineering Point of View)



1) Intra-body Channel Characterization
(Area of Interest)

Establish efficient communication links between intra-body bionanosensors

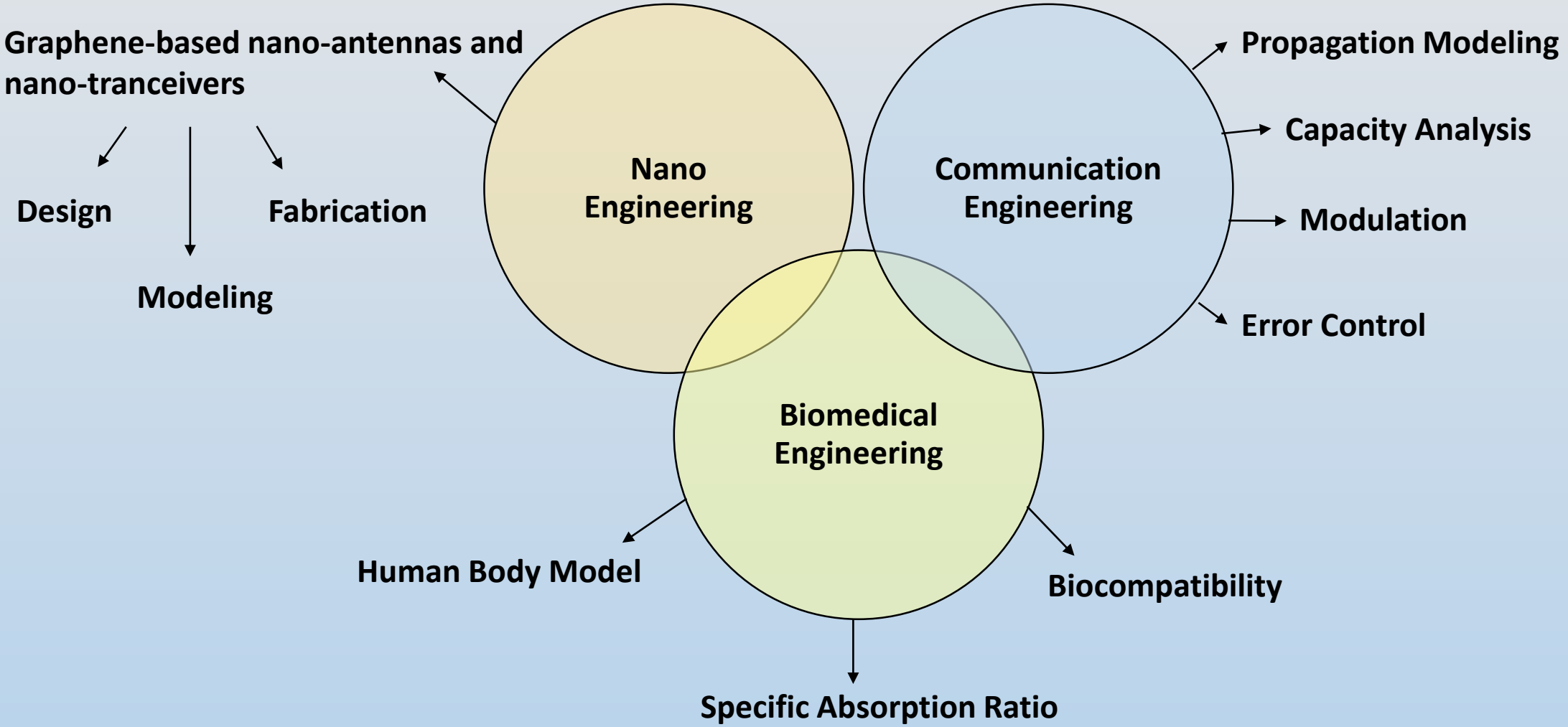
2) Energy Harvesting

Minimize the nanonetwork energy consumption through energy harvesting bionanosensors

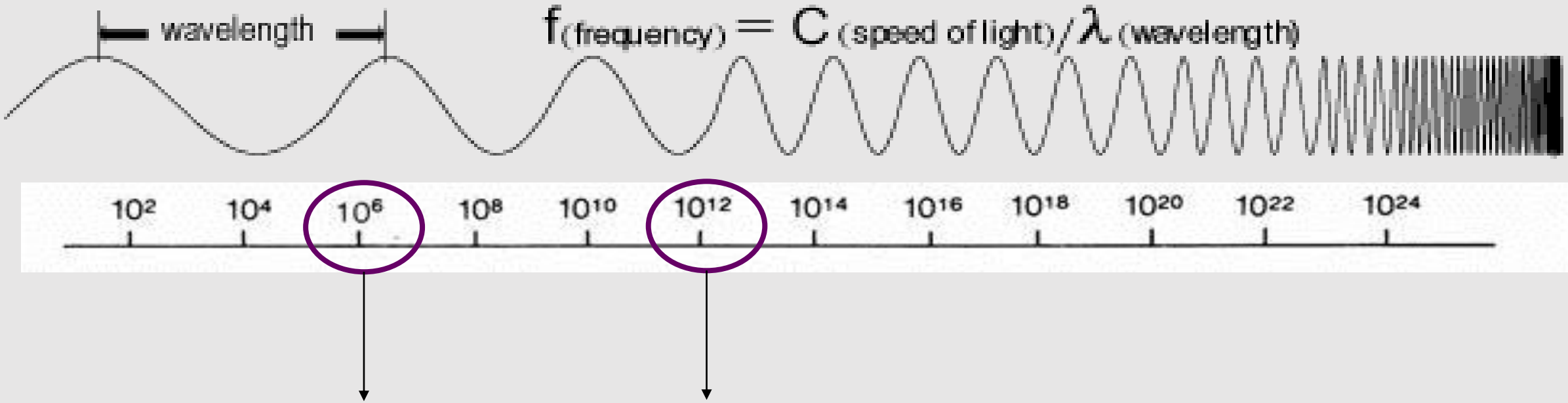
3) Security Issues

Establish secure links among intrabody bionanosensors

Establish Efficient Communication Links Between Nanonetworks



- **The Electromagnetic Spectrum**



Band # 1 : HBC Via Galvanic Coupling

Band # 2 : THz Intra-Body Communication

Presentation Outline

- Human Body Communication

  - Capacitive Coupling

  - Galvanic Coupling

- In Vivo THz Intra-body Communication

- Conclusions and Future Directions

Intra-Body Communication:

Human Body Communication Via Galvanic Coupling

- HBC is a novel data transmission technique using the human body itself as the transmission medium or channel.
- HBC has been introduced by the IEEE as a third physical layer.
- This method is set to eliminate both bulky cable and wireless antenna from medical monitoring communication devices.
- The inhibition of communication to the person's proximity in IBC users prevents the energy from being dissipated into the surrounding environment
- Compared to RF wireless techniques, HBC potentially provides lower transmission power (less than 1.0 mW) with data rates of more than 100 kbps.
- The operating frequency band of HBC is centered at 21 MHz with channel frequency bandwidth of 5.25 MHz and scalable data rates of 164-1312.5 kbps

Intra-Body Communication

- IBC can be classified into two basic coupling types (i.e. how the electrical signals are transmitted):

  - Capacitive coupling (Near-electric field)

  - Galvanic coupling (Waveguide)

Capacitive Coupling

- Capacitive coupled IBC is based on the capacitive coupling of the human body to its surrounding environment.
- The signal is generated between the body channel transceiver by making a current loop through the external ground.
- The signal electrode of the transmitter induces the electric field in to the human body.
- The induced electrical signal is controlled by an electrical potential and the body acts as a conductor with the ground as the return path.

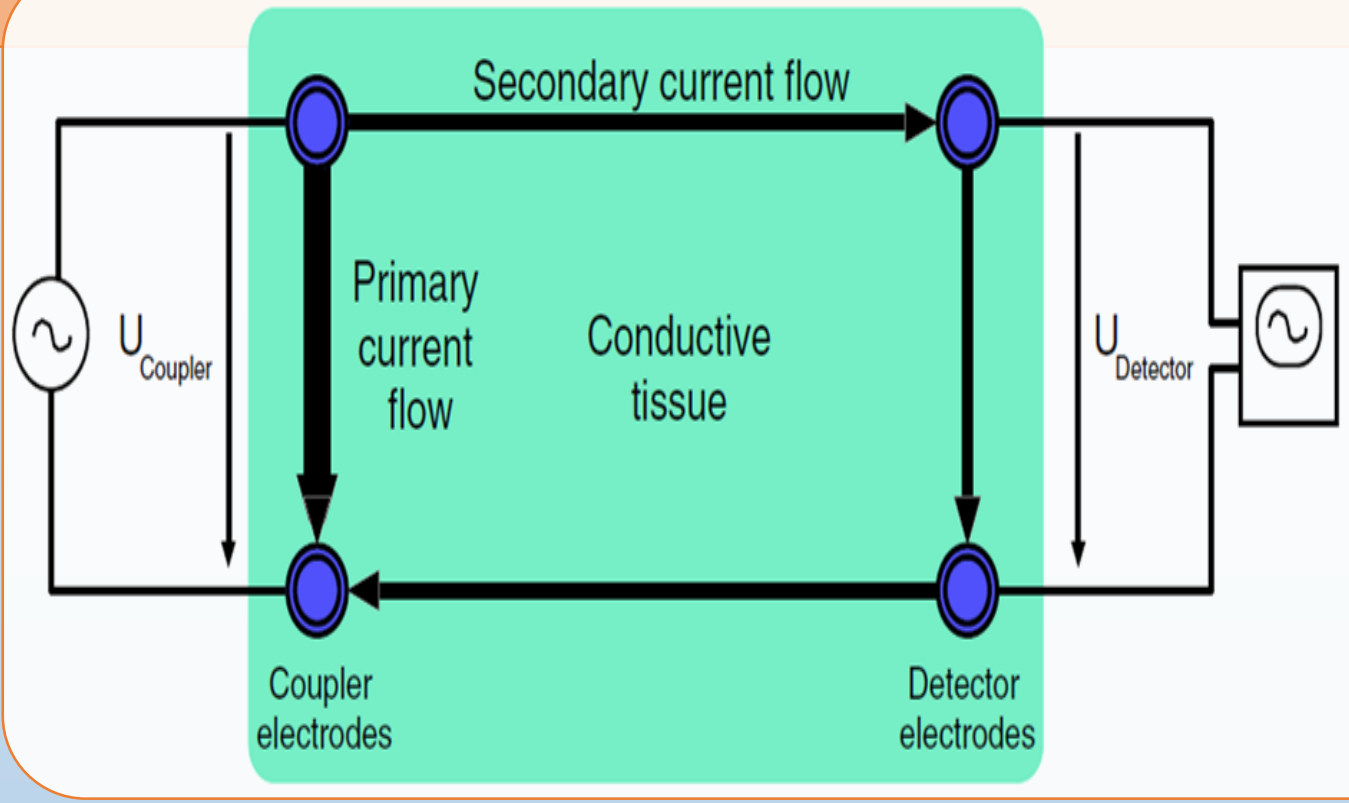
Intra-Body Communication

Galvanic Coupling

- Galvanic coupling is achieved by coupling alternating current into the human body.
- It is controlled by an AC current flow and the body is considered as a transmission line (waveguide).
- An electrical signal is applied differentially between the two electrodes of the transmitter.
- Major propagation of the signal occurs between the two transmitter electrodes and a largely attenuated signal is received by the two receiver electrodes.
- The small current results in a differential signal between the electrodes.
- In general, the ion content in the human body is the carrier of information in the galvanic coupling method.

Intra-Body Communication

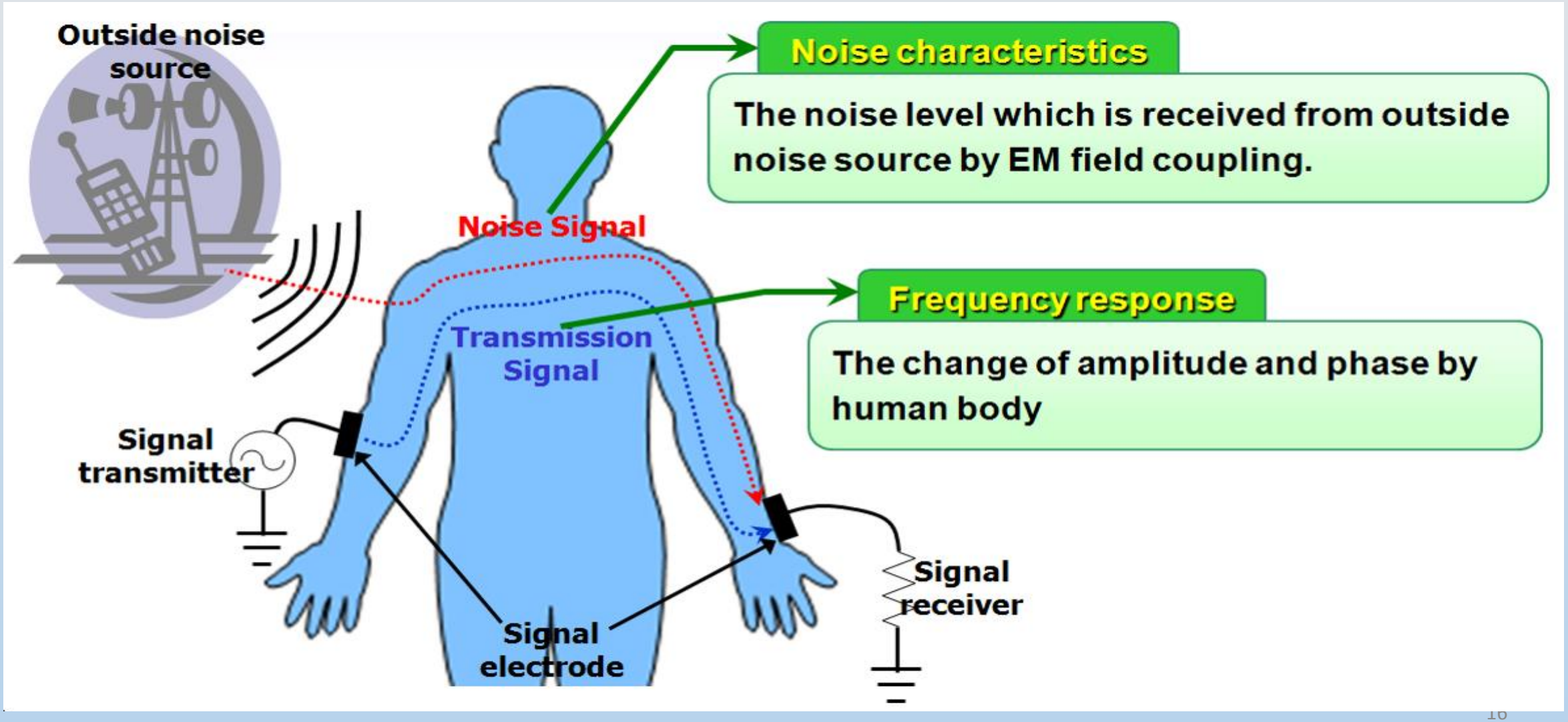
Galvanic Coupling (Mechanism)



The setup to achieve galvanic coupling involves:

- Injecting an alternating current in the coupler between the two electrodes.
- The detector unit senses the transmitted signal through another two electrodes.
- The attenuation factor changes according to the dissimilar human body tissues which exhibit different electrical properties.

Paper Contribution:
Human Body Channel Characterization

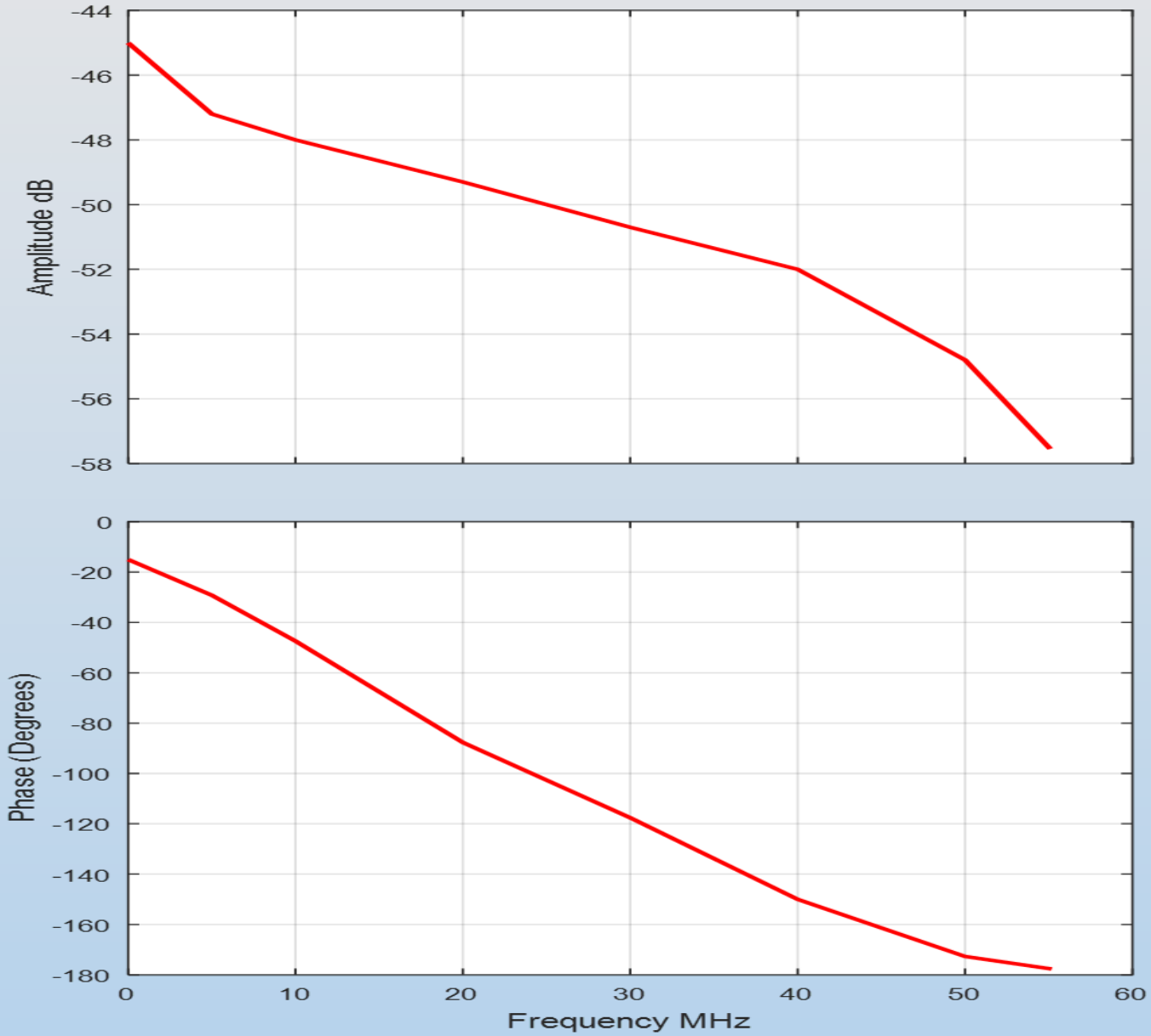


Paper Contribution:
Human Body Channel Characterization

To study the human body as a communication channel:

- A voltage signal is induced through a pair of electrodes.
- A 2x2 cm^3 electrode pair located at the fingertips of each hand is used.
- The transmission distance between the transmitter and receiver is 150 cm.
- Because the human body is a lossy dielectric medium, an attenuated voltage will be induced on the receiver load.
- The voltage signal experiences a change in its amplitude and phase due to the capacitive loss associated with the components of the human body.
- The frequency response in the range 5 MHz-50 MHz.

Simulation Results : Frequency Response



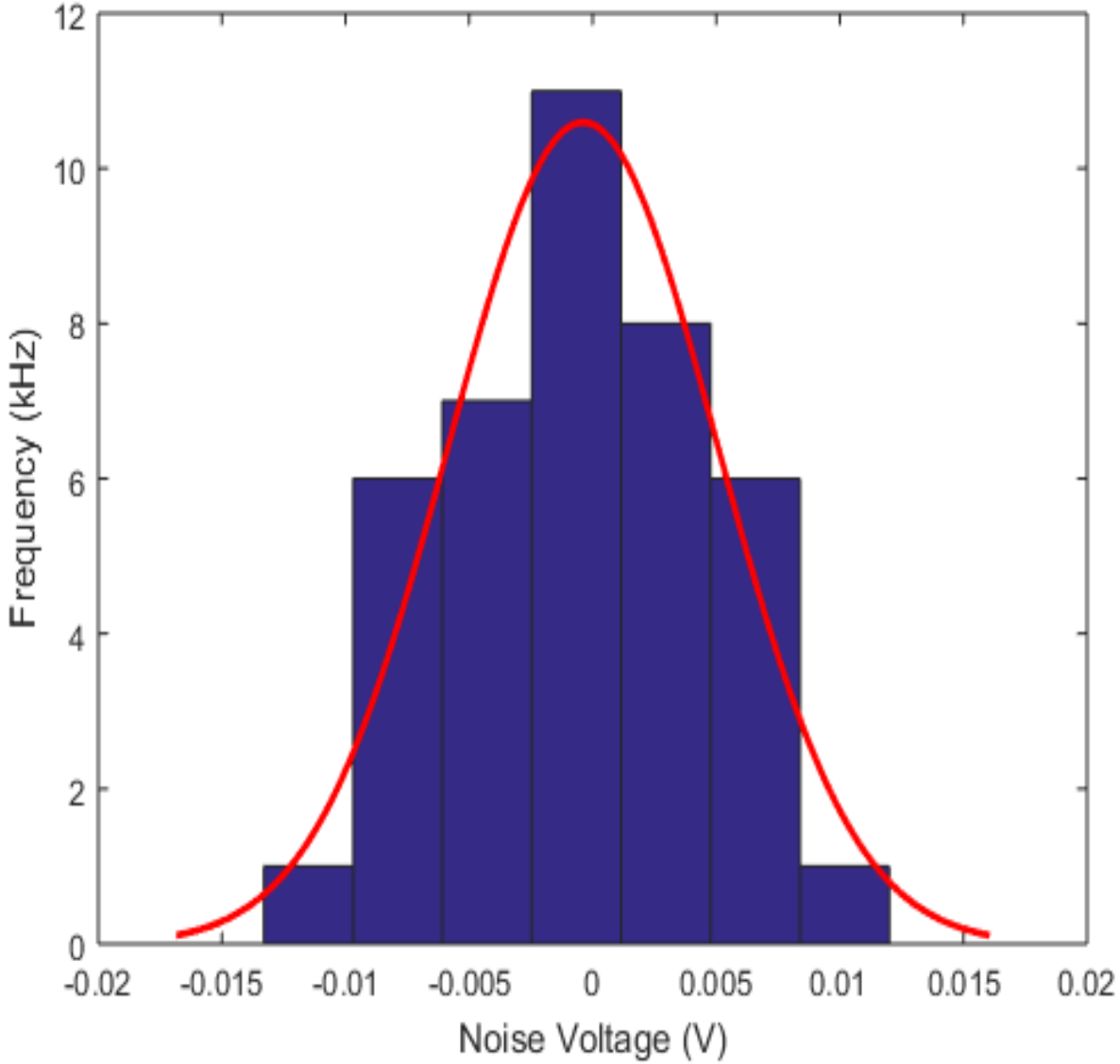
The amplitude of the received signal decays with increased frequency indicating increased attenuation effects.

It can be concluded that the received signal strength (RSS) attenuates to the nano-volt or even pico-volt range, making reception very difficult.

The propagation speed reduces as the electromagnetic (EM) wave passes through an inhomogeneous medium.

This results in time dispersion, that differs with each organ and body tissue.

Simulation Results: Noise Characterization



The users of HBC are vulnerable to EM radiation from several electronic devices during data transmission.

This radiation results in noisy data reception.

The noise characteristics vary according to site and time, which imposes the need for a statistical prediction exact.

Results demonstrate that the measured noise can be approximated as a Gaussian distribution with zero mean and variance of 2.55×10^{-5}

Presentation Outline

- Human Body Communication
  - Capacitive Coupling
  - Galvanic Coupling
- ***In Vivo THz Intra-body Communication***
- Conclusions and Future Directions

Why THz ?

Higher Frequencies

↓

Shorter Wavelengths

↓

Capture Molecular Interactions

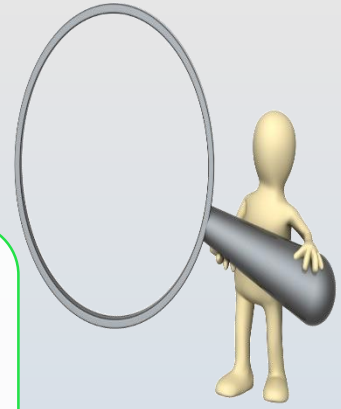
↓

Nanoscale Level

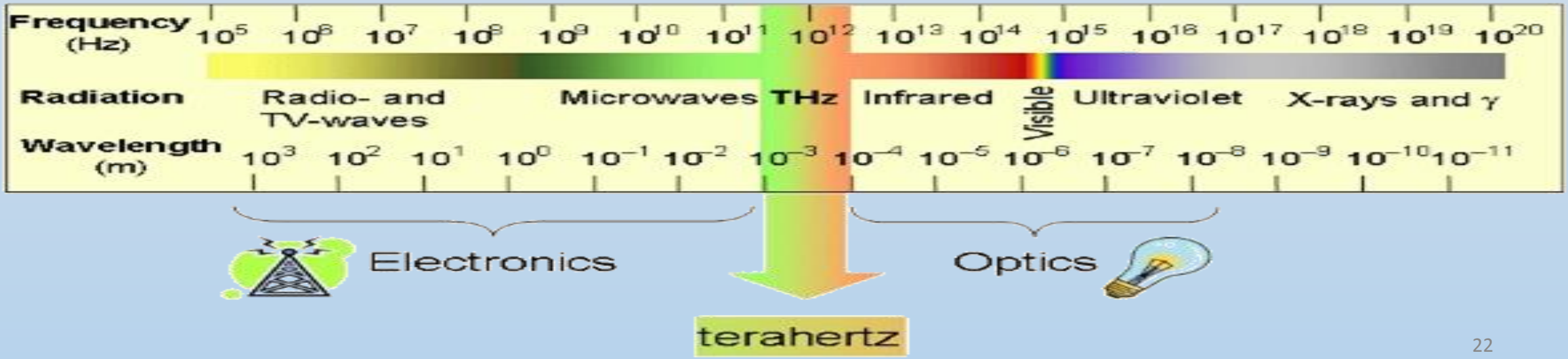
↓

Nanotechnology Enables the Development of Novel Nanosensors

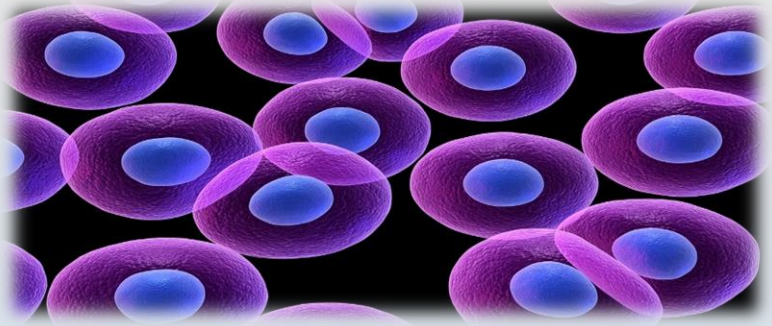
Facts about the THz Band

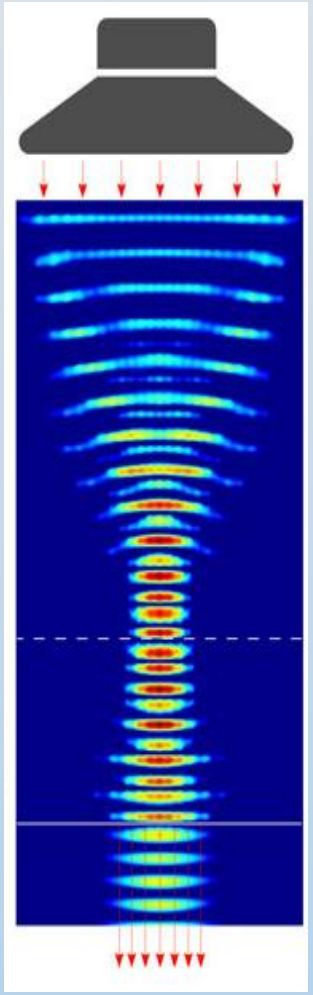


- Terahertz Band (0.1-10 THz) communication is envisioned as a key technology to satisfy the increasing demand for higher speed wireless communication.
- However, the THz spectrum, known as the THz gap, has not been fully exploited and explored.
- The THz technology is a fast growing field with applications in biology and medicine.
- The non-ionizing nature of the THz makes it appealing for health applications.



Communication Modes in Nanonetworks





Molecular Communication

- *Based on the exchange of molecules to transmit information.*
- *Used by cells to exchange information and coordinate their actions.*

Ultrasonic Communication

- *Utilization of high frequency acoustic waves.*
- *Yet, the size and power limitations of ultrasonic transducers pose a challenge on their integration with biological nano-sensors.*

Adopted Communication: Electromagnetic Wireless Nanosensor Networks

- Evolution of Concept

- From the EM perspective, miniaturization of conventional metallic antenna results in high resonant frequencies.

  f_0 is approximately 150 THz (10^{12} Hz).

- Therefore, the feasibility of electromagnetic (EM) communication in nanonetworks would be compromised due to:

Limitation 1
High propagation Loss: $A \propto f^2$

$$\frac{A(150\ THz)}{A(2.4\ GHz)} = 3.9 \times 10^9 \sim 100\ dB$$

Limitation 2
Low transmission power of nano-machines

$$P_{max} = \frac{E_{cap}}{\Delta t}$$

Limitation 3

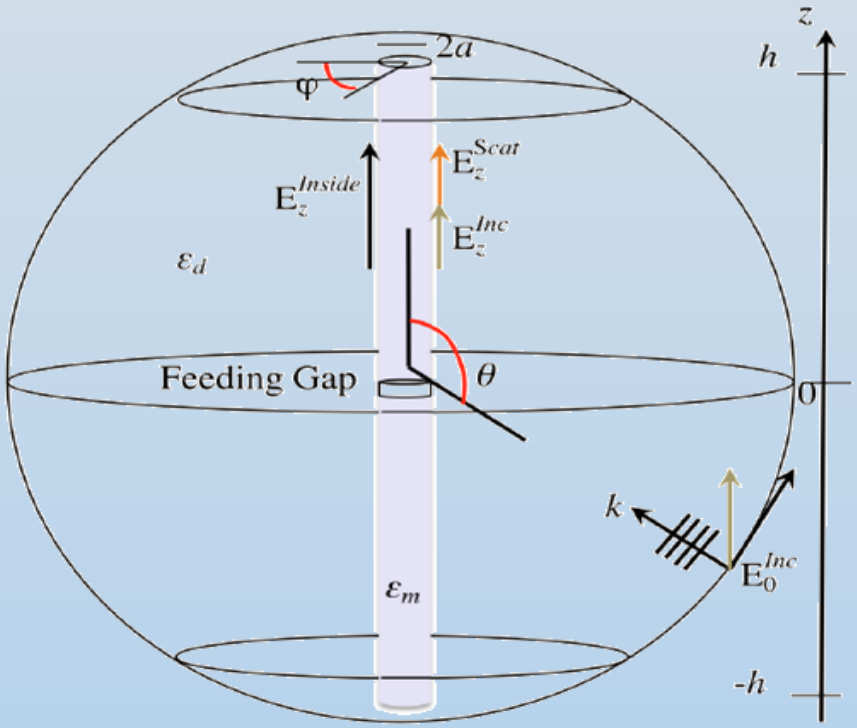
Lack of nano-transceivers able to operate at these frequencies

Adopted Communication: Electromagnetic Wireless Nanosensor Networks

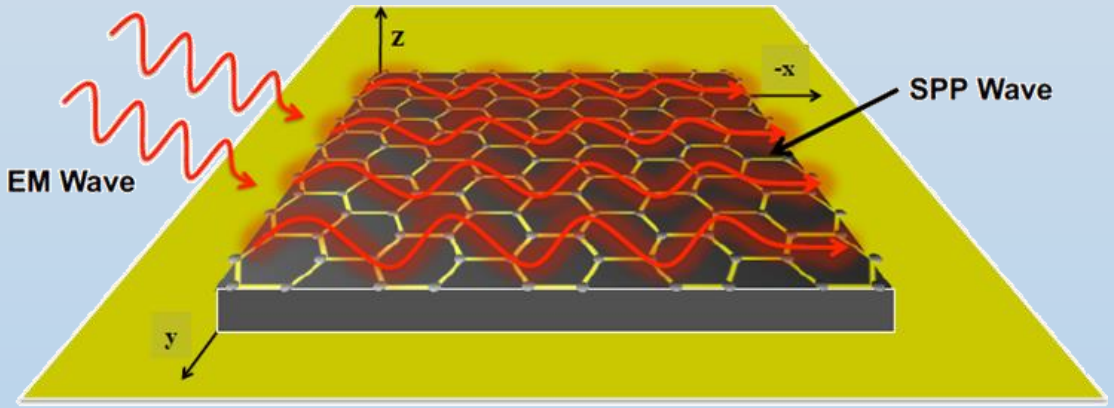
- Evolution of Concept

- Although at such frequencies metals do not behave as PEC, **they exhibit complex conductivity**
- This enables the propagation of confined EM modes at the surface of the antenna. (Surface Plasmon Polariton Waves)
- This led to the development of :

Novel Plasmonic Nanoantenna



Graphene-based Plasmonic Nanoantenna



In Vivo Nano-Communication in WBANs

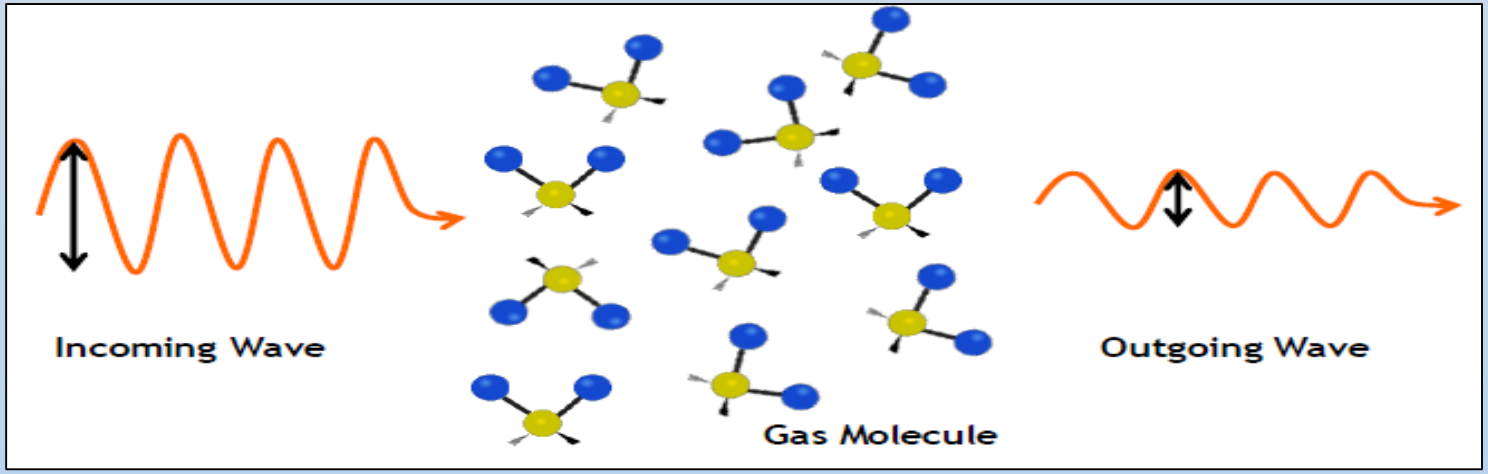
- The properties of the THz band open a new era and interest because of its **non-ionization hazards** for biological tissues.
- The feasibility of using THz to communicate has already been validated [1].
- However, *in-vivo* communication at THz **has not been** studied for a tissue model

Motivation for current research: Is it possible for THz waves to propagate *in vivo* ?

[1] J. M. Jornet and I. F. Akyildiz, "Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band," in *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211-3221, October 2011.

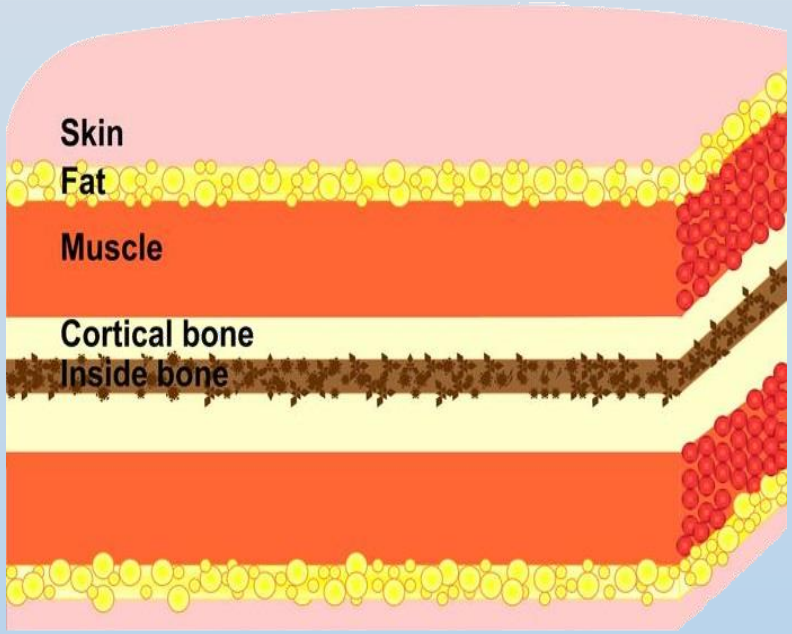
In Vivo Nano-Communication in WBANs

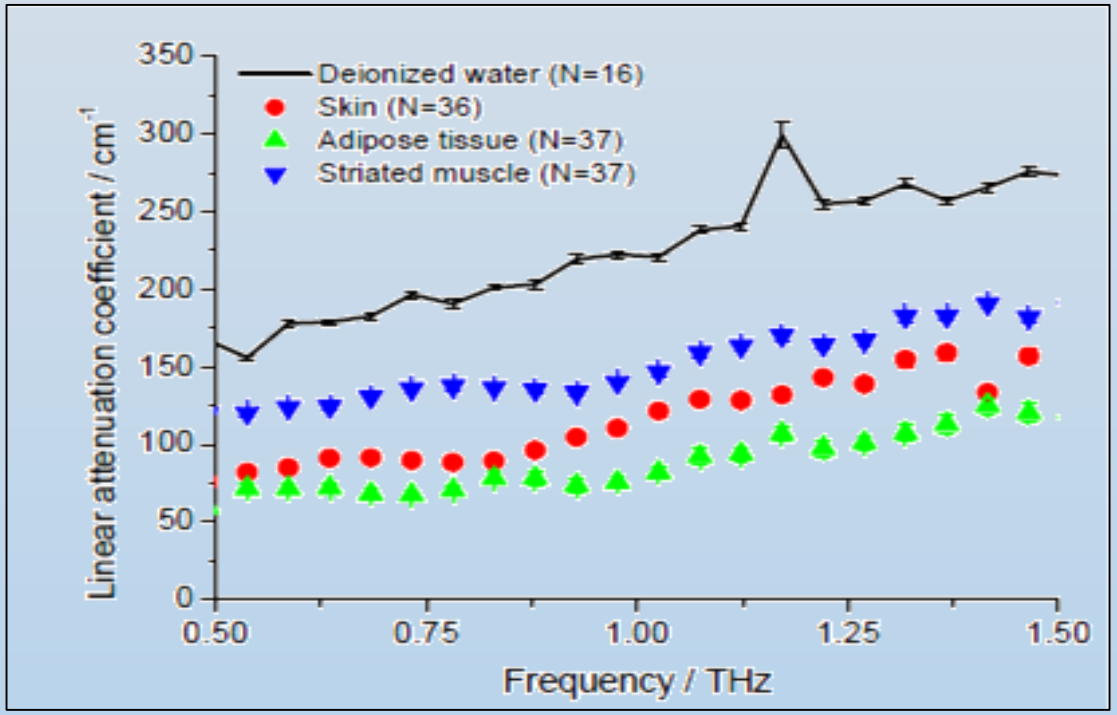
- **A channel model** provides an analytical description of such effects and gives a way to compute the
  - Attenuation (Path Loss) **due to the transmission of waves**
  - Noise Model
  - Channel Capacity
- Channel models for lower frequency ranges (MHz, GHz) cannot be used in the THz Band.
  - Do not capture the impact of molecular absorption.



In Vivo Nano-Communication in WBANs

- This work studies *in-vivo* communication at THz frequency for a biological tissue model constituting of bone, muscle, fat, and skin.
- The optical parameters of human tissues up to 1.5 THz are demonstrated in [2].
- The path loss is calculated and the possibility of THz waves to propagate *in-vivo* for different materials is checked.





[2] Fitzgerald, A. J., et al. "Catalogue of human tissue optical properties at terahertz frequencies." Journal of Biological Physics 29.2-3 (2003): 123-128.

1) Path Loss Model

$$PL[dB] = PL_{spread} + PL_{absorption}$$

$$PL_{spread} = -10 \log_{10} \left(\frac{\lambda_g}{4\pi d}\right)^2$$

$$\lambda_g = \frac{\lambda_0}{n}$$

$$PL_{absorption} = -10 \log_{10} e^{-\alpha d}$$

$$\alpha = \frac{4\pi K}{\lambda_o}$$

- **The refractive index n**

$$n = \sqrt{\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'^2}{2}}$$

- **The extinction coefficient K**

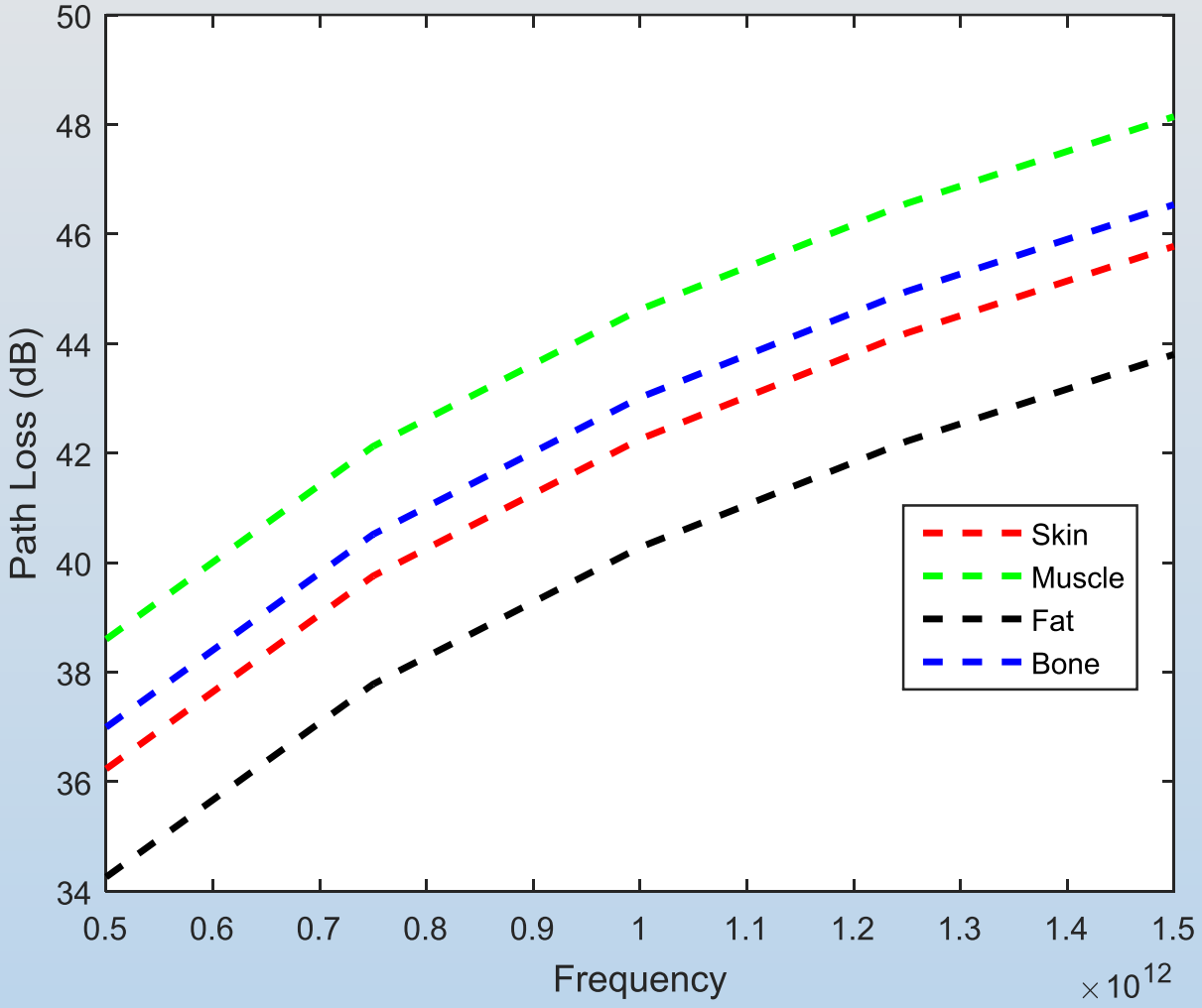
$$K = \sqrt{\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'^2}{2}}$$

- **Permittivity**

$$\varepsilon = \varepsilon' - j\varepsilon''$$

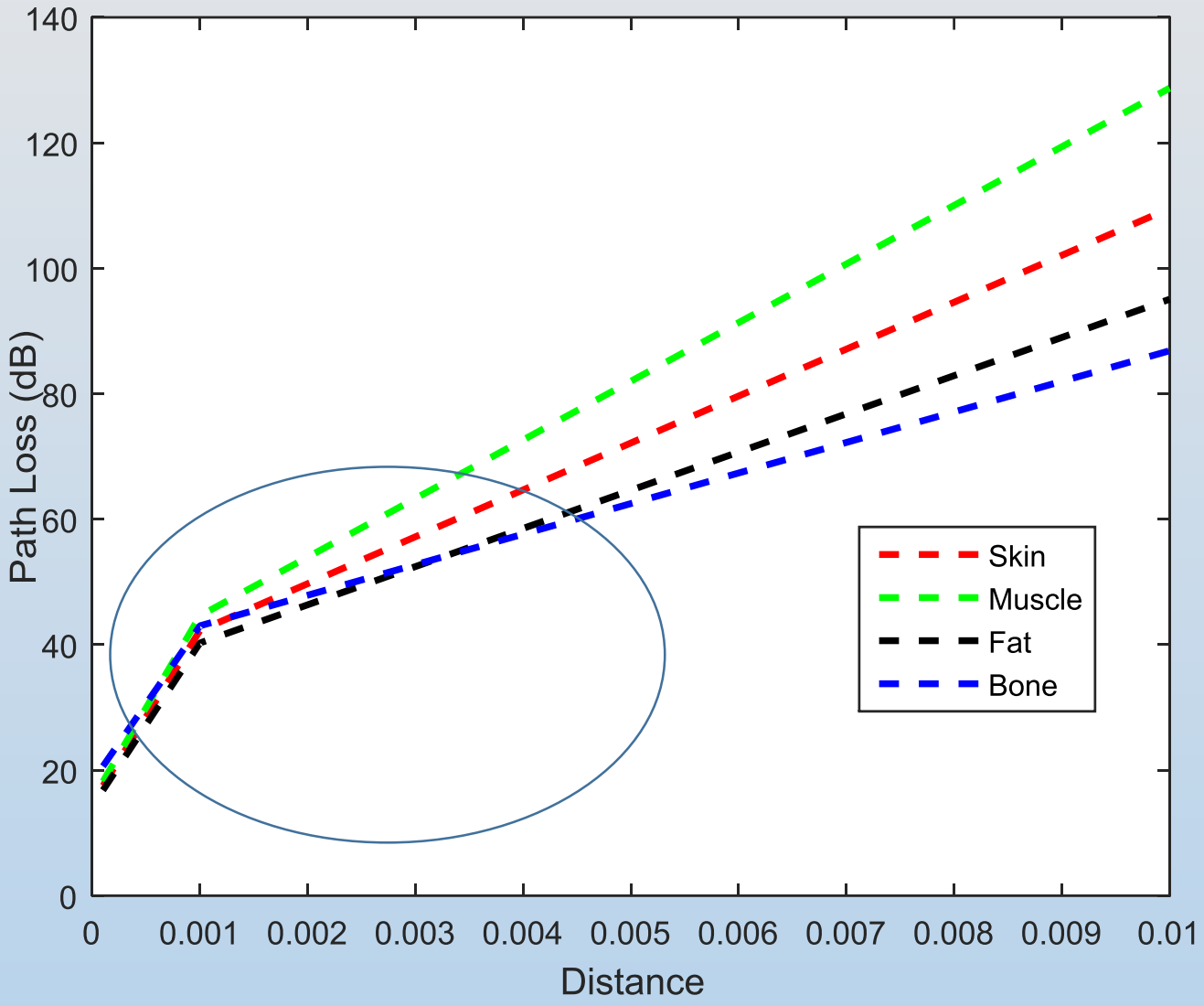
Tissue	n
Skin	1.69
Bone	2.49
Fat	1.58
Muscle	1.79

Simulation Results



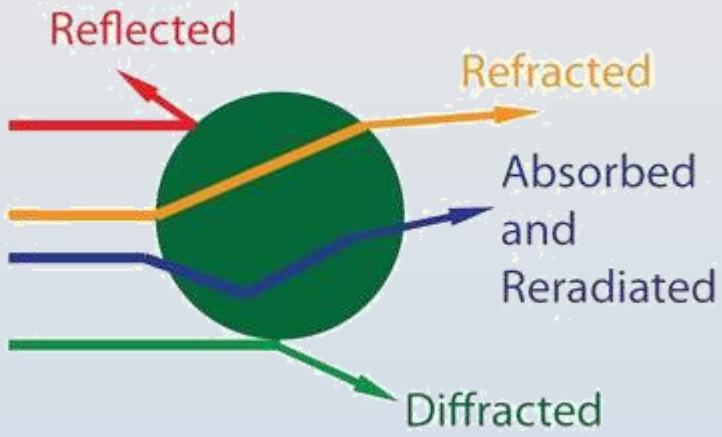
The path loss between 0.5 and 1.5 THz at a distance of 1mm is around 40 dB.

Simulation Results



At 1 THz, the path loss between 1 mm and 1.5 mm ranges between 36 dB and 40 dB, for the different body parts.

1) Path Loss Model



- **Path Loss Model presented is “Basic”**
- **It lacks the incorporation of theories of :**

Diffractions

Reflection

Scattering

NLOS Propagation Model

2) Molecular Absorption Noise Temperature

- **Emissivity of the channel**

$\varepsilon(f,d) = 1 - \tau(f,d) = 1 - e^{-\alpha(f)d}$

$\tau \therefore$ Transmittance of the medium

- **Noise Temperature due to molecular absorption**

$T_{mol}(f,d) = T_0 \varepsilon(f,d)$

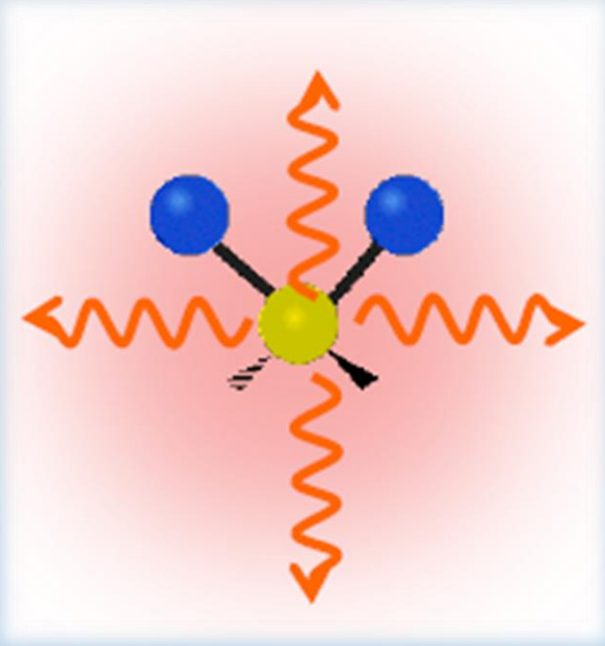
- **Total System Noise Power**

$T_{noise} = T_{sys} + T_{ant} = T_{sys} + T_{mol} + T_{other}$

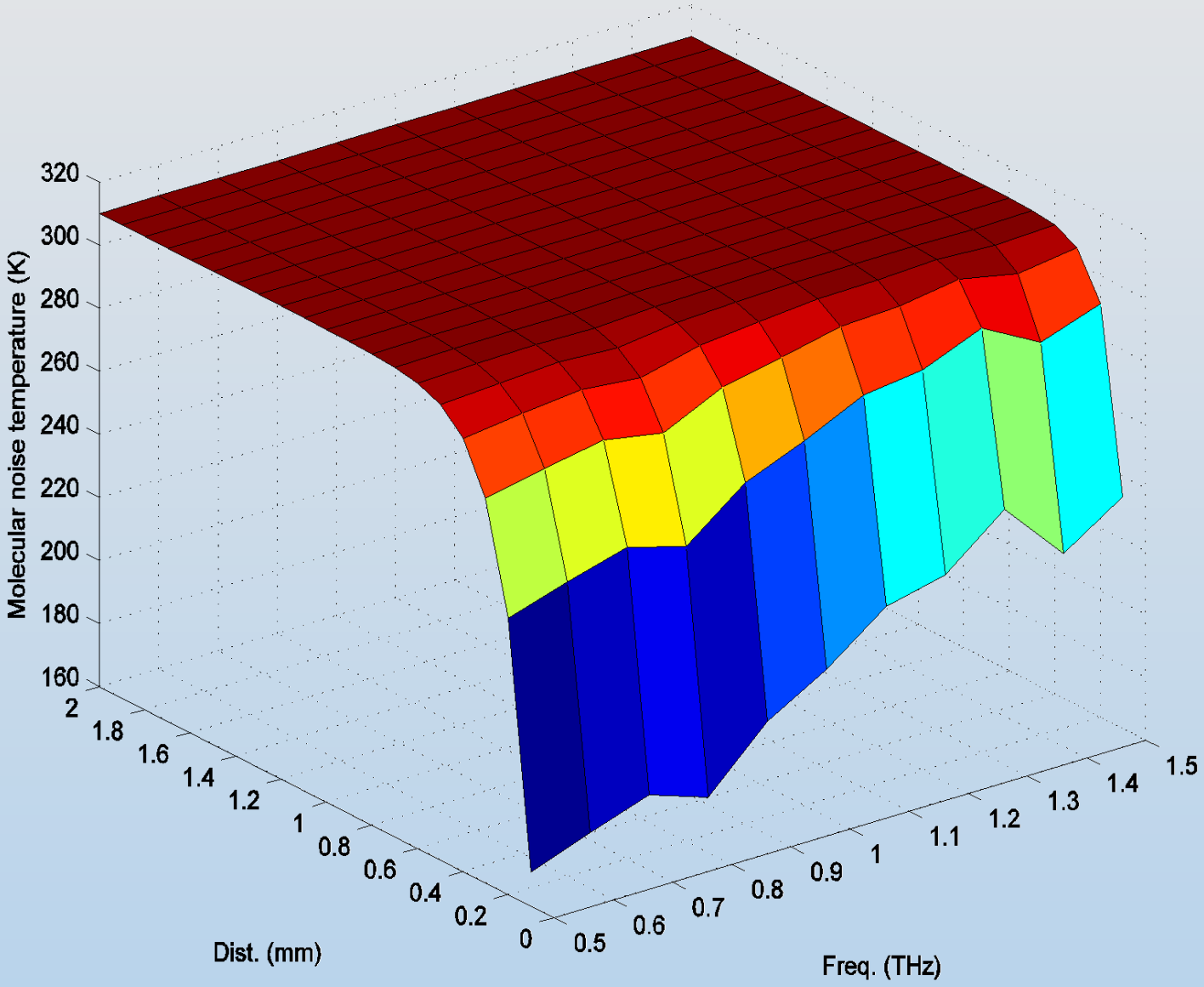
T_{sys}= system electronic noise temperature
T_{ant}= total antenna noise temperature
T_{mol}= molecular absorption noise
T_{other}=additional noise sources

- **Equivalent noise power at the receiver**

$P_n(f,d) = \int_B N(f,d)\,df = k_B \int_B T_{noise}(f,d)df$



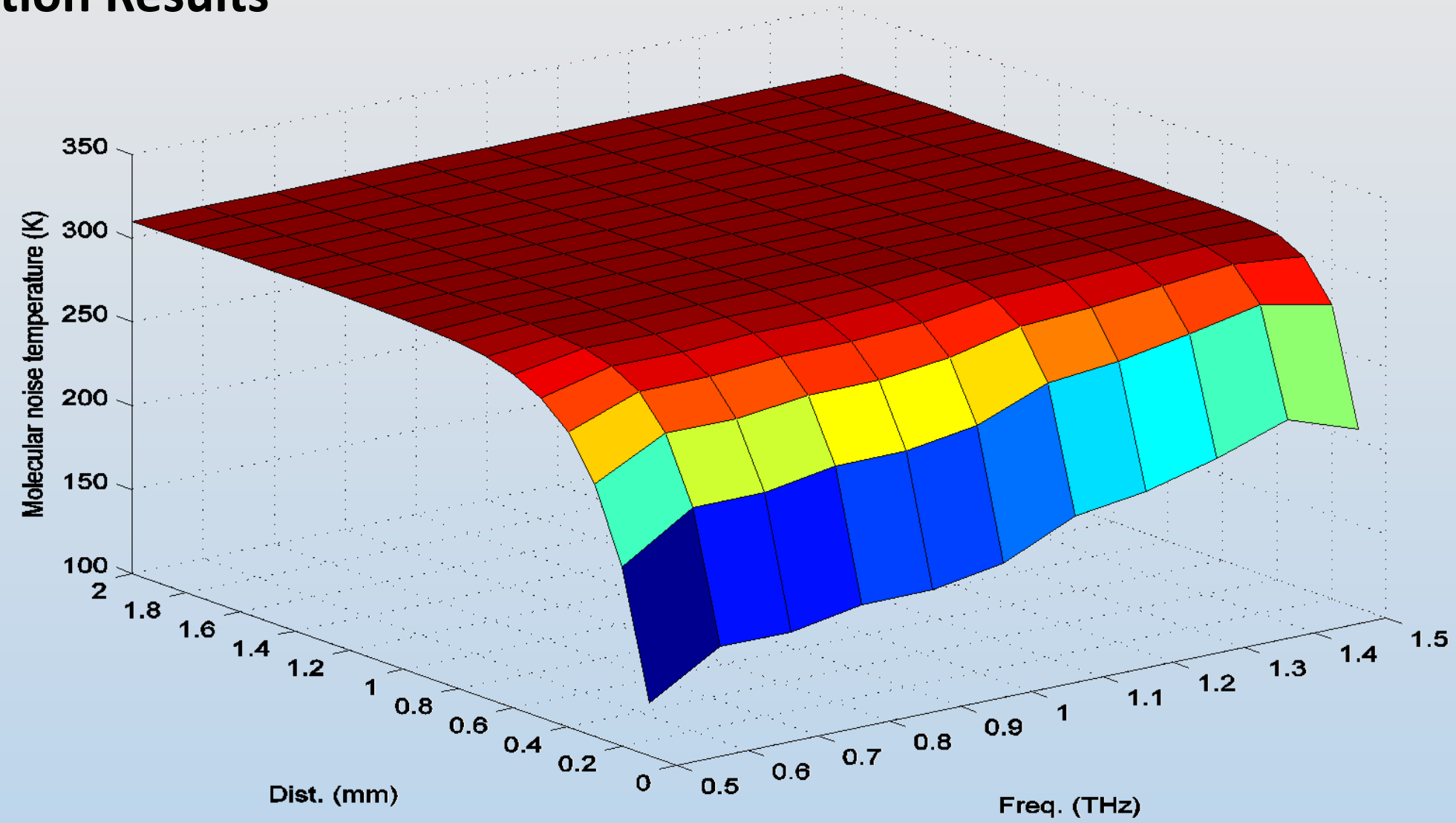
Simulation Results



Molecular noise temperature in Skin

At the level of millimeters, the molecular noise temperature isn't tremendously high (approximately 310 K).

Simulation Results



Molecular noise temperature in Fat